Microscreen-Based Replication of Electroforming Micromolds

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Abstract

Novel technology is presented which allows the rapid replication of electroforming plastic micromolds. This technique incorporates microscreens into hot embossing or injection molding processes to produce sacrificial molds with conducting bases and insulating sidewalls. Both contiguous and non-contiguous features can be electroformed from these molds. Process parameters including the microscreen geometry and the use of multiple porous metal inserts are discussed.

1. Introduction

LIGA technology has the potential to provide microsystem solutions to various problems for which silicon MEMS technology is simply not suitable [1,2]. However, the successful commercialization of high aspect ratio LIGA microstructures requires economical replication technologies to eliminate repetitive synchrotron and development steps. While hot embossing and injection molding processes using LIGA produced microstamps have enabled the replication of plastic microstructures [3,4], many applications require the more challenging replication of metal parts and structures. These applications include high reflectivity micromirrors, high current microswitches or relays, high mass components for acceleration or orientation sensors, and low thermal expansion micro-optical positioning devices. One approach to the replication of such metal microstructures is the production of plastic molds which contain a conducting electroformable base.

In the production of replicate electroforming molds, conductive bases and insulating sidewalls are critical requirements for high aspect ratio designs to prevent premature cavity closure during plating [5]**.** A specialized example of a replicated electroplatable mold was reported in which an array of micro-nozzles was replicated by first infusing a curable liquid silicone rubber into a closed mold [6]. The base plate of the mold included dovetail inlets and cavities to hold the rubber against the bottom plate during demolding and the base plate was incorporated into the final electroformed device. Other researchers explored the use of cast PMMA substrates containing a non-conducting layer and a filled, conducting layer [7]. The PMMA bilayer was embossed in such a way that the microstamp features penetrated through the insulating layer and into the filled, conducting layer. Also reported was the use of cast PMMA substrates coated with metal films which were deformed during embossing to provide electroplatable molds [8]. Various modifications were used to enhance these processes [9,10]. Some of these processes were limited to the replication of contiguous features only.

This paper presents a novel technique that allows the rapid replication of a wide range of electroforming micromolds. This technique incorporates microscreens into the hot embossing or injection molding processes to produce sacrificial molds with conducting bases and insulating sidewalls. Unlike the methods discussed above, this technique uses commercially available metal microscreens, does not require the presence of specific features or geometries in the final electroformed part, has fast cycle times amenable to volume production, and can be used for both contiguous or non-contiguous microparts.

2. Microscreen-based Replication of Electroforming Molds

While the general approach described here can be carried out with various plastic molding techniques, this paper will focus on hot embossing and injection molding.

In hot embossing, a metal microscreen is placed on top of a thermoplastic disk with a microstamp contacting the opposite side of the screen (Fig. 1a). The embossing chamber is evacuated and the assembly is heated to a temperature above the resin Tg. The microscreen is pressed by the stamp into the softened plastic disk, forcing the resin to flow through the holes of the screen and fill the microstamp cavities (Fig. 1b). Upon cooling and demolding, an electroforming plastic mold is produced with insulating plastic features mechanically locked to the metal screen (Fig. 1c).

In injection molding, the metal microscreen is placed on top of a microstamp in a vertical injection molding machine (Fig. 2a). One or more additional sheets of macroporous metal may be placed on top of the microscreen to mechanically secure the microscreen against the microstamp after mold closure and to redirect the plastic flow within the mold cavity. The closed mold is evacuated and the hot thermoplastic injected (Fig. 2b). After cooling and ejection, the resulting electroforming micromolds are similar to those produced by embossing (Fig. 2c).

The micromolds replicated by either of these techniques can then be electroplated, lapped, and the metal parts released from the microscreen by dissolution of an intermediate layer of a sacrificial metal such as copper.

3. Experimental Results

Chemically etched stainless steel microscreens from BMC Industries Inc., are suitable for these processes and are available in various patterns. Two different microscreens were evaluated. One screen, BM 542, is a 125 micron thick stainless steel sheet with a regular hexagonal pattern of tapered holes with a 300 micron pitch. The holes are approximately 200 microns in diameter on one side and 150 microns in diameter on the opposite side. The other screen, BM 218, is a 50 micron thick stainless steel sheet with a regular hexagonal pattern of straight holes, approximately 75 microns in diameter, with a 150 micron pitch. PMMA resin pellets from Atofina Chemical with a range of melt flow values were used directly for the injection molding trials or were prefabricated, using simple chase molds, into disks 1/8 inch (0.3175 cm) thick x 3.5 inch (8.89 cm) diameter for the hot embossing trials.

The microstamps used in these experiments were nickel plated on three inch 7.62 cm) diameter circular tool steel bases and were fabricated through the LIGA process at Sandia National Laboratories, Livermore, CA, as described elsewhere [11,12]. Stamps with either 95 or 170 micron deep features in a pattern containing gears, wedges, channels and other designs were used (Fig. 3). The same interchangeable microstamps were used for both the hot embossing and injection molding processes.

Embossing experiments were carried out with custom designed tool steel dies fastened within an Instron 1000 Mechanical Test Frame. The bottom die was equipped with vacuum and thermocouple attachments and fixturing for the thermoplastic substrate while the top die contained fixturing for the microstamp. Both dies were heated with platens.

Injection molding experiments were carried out on a 60 ton Nissei vertical injection molding machine (Model TH60-5VSE with 22 mm screw and NC-9300T controller) equipped with a customized mold base to accommodate interchangeable microstamps. The mold base was also equipped for vacuum evacuation of the mold cavity. The machine nozzle is spring loaded to avoid resin drip between injections.

In a typical embossing experiment, a microscreen disk approximately 3.7 (9.398 cm) inches in diameter was placed on top of a PMMA resin disk. A circular metal frame was used to secure both the microscreen and resin disks within the bottom die. The microstamp was fastened in a frame on the top die. The matched dies were then closed, evacuated, and heated to a temperature above the Tg of the resin. When the target temperature (typically about 160-175°C) was reached, the top die was forced into the softened resin at a pressure of approximately 125 psi. The assembly was then air cooled and the embossed electroforming mold removed. Figure 4 shows an overview of an embossed electroforming mold containing the microscreen and an SEM of one of the mold features.

In a typical injection molding experiment, a microscreen disk approximately 3.5 inches (8.89 cm) in diameter was placed on top of the microstamp fastened within the bottom mold base. Additional macroporous metal disks of various types such as porous nickel foam (Inco, Ltd., one mm thick foam with pores 500 microns in diameter or larger), simple screen door meshes, or perforated steel sheets with holes 1/8 to 1/4 inches (0.3175 to 0.635 cm) in diameter were placed on top of the microscreen. The mold was then closed and evacuated. Mold and barrel temperatures were set according to the resin grade used and were typically at the higher end of the temperature range suggested by the resin manufacturer for standard injection molding. After injection and cooling, the mold was opened and the plastic/metal part ejected. Cycle times were generally about 1-2 minutes. Figure 5 shows details of an injected electroforming mold.

Prior to electroforming, the molds were electrolytically cleaned in a 70% v/v sulfuric acid solution at a current density of 150 A/ft^2 for three minutes. The fresh stainless steel surfaces within the molds were given a Wood's nickel strike in a nickel chloride bath at 50 A/ft^2 for three minutes followed by a copper seed/release layer deposited from a copper sulfate bath at 15 A/ft^2 for ten minutes. The molds were then placed in a nickel sulfamate electroplating bath at 15 A/ft^2 and the features were overplated. The excess nickel was removed by lapping and polishing (1 micron grit), the PMMA was dissolved in acetone, and the nickel parts were released by etching the copper layer in a chromic/sulfuric acid etch. Figure 6 shows electroplated test features obtained from an embossed mold prior to release of the parts from the screen.

4. Discussion

During embossing or injection molding with microscreen inserts, the resin is forced to flow through the screen holes into the randomly aligned microstamp cavities on the other side of the screen. The desire for numerous and large holes in the microscreen to maximize resin flow into the cavities is obviously at odds with the later desire for an optimal electroforming base. Depending on the screen used and the screen and stamp alignment, many microstamp feature cavities are accessible to the flowing resin only through a series of partially blocked holes as is evident from the figures. It is critical that the screen be pressed securely against the microstamp during these processes to prevent resin flow over those screen areas which need to remain bare and provide the electroforming base. It is equally critical that the resin is able to completely fill the microstamp cavities and that the screen is not deformed during this process.

The relatively gentle embossing process proved amenable to both the thin and thick microscreens evaluated and the orientation of tapered holes in the thicker screen did not affect the quality of the replicated features. Careful adjustment of the resin temperature and melt flow properties allowed the replication of high quality electroforming molds from either screen and from both of the microstamps used. PMMA resins with a range of melt flow values were used successfully by adjusting the embossing temperature.

For injection molding, the addition of macroporous metal sheets proved to be an important component of the replication process. Without these macroporous sheets, the microscreen was often deformed and pushed into some of the microstamp feature cavities by the force of the injected plastic. The added macroporous backing sheets appear to moderate and redirect the resin flow and were found to significantly improve the quality of the replicated molds. Short shot studies and other work are in progress to fully characterize the role of such macroporous sheets in this process and to optimize the micro/macro screen combinations used. Sealing of the microscreen itself against the stamp cavities was again very effective as shown in Figure 5.

A further advantage of the steel macroporous sheets in the injection molded replicates was elimination of the warping often observed in replicated molds without this backing as they continued to cool after ejection from the machine. Planarity in the electroforming mold is critical for the subsequent plating and lapping steps. Such warping is caused by the mismatch in the coefficient of thermal expansion of the resins and the microscreens. It was less evident in the embossed molds which were more fully cooled before removal from the fixturing.

Nickel electroforming experiments demonstrated the ability to produce solid, fully replicated nickel microparts even when using microscreens with the larger hole size (Figs. 6 and 7). Even though the PMMA-filled microscreen holes at the bottom of the electroforming cavities are insulating, the electroplated metal was able to effectively fill the areas over these holes. Overplating and lapping removed any evidence of surface dimpling due to the holes in the microscreen plating base.

When the microstamp design permits, it is clearly desirable to use screens with the larger hole size, and the BM 542 has been used for most of the work reported here. The BM 218 microscreen with smaller, 75 micron, holes was also used successfully and the needs of any particular stamp design will drive the screen selection. While screens with dense patterns of even smaller holes might be desirable, their availability is limited by the wet metal etching process used to produce such commercial screens. As a result, the smallest hole diameter achievable is on the same order as the screen thickness and would require the fabrication of extremely thin and unacceptably fragile screens. Other types of microporous metals such as frits have been evaluated but have not matched the performance of the microetched screens.

It is expected that prudent design rules can avoid many small isolated features which might be problematic in the processes described here or allow their attachment to a larger, anchor structure.

This technology should enable the rapid and cost effective replication of metal LIGA parts by restricting synchrotron exposure and development to only the initial fabrication of the microstamp.

5. References

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6. Acknowledgements

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Figures

Figure 1: Schematic of mold replication by hot embossing through a microscreen in (a) the initial configuration and (b) during the embossing step. Schematic (c) of replicated mold.

Figure 2: Schematic of mold replication by injection molding through a microscreen in (a) the initial configuration and (b) during the injection step. Schematic (c) of replicated mold.

Figure 3. Optical photograph of microstamps made by plating nickel patterns on tool steel bases and SEM close-up of a 95 micron deep nickel test feature.

Figure 4. Low magnification optical photograph of an embossed PMMA electroforming mold and SEM close-up of 170 micron deep gear feature.

Figure 5. SEM photographs of an injection molded PMMA electroforming mold with 95 micron high features. a) Internal gear mold. b) Resolution test wedge features. c) Isolated posts. d) Sandia's logo, a Thunderbird.

Figure 6. SEM photographs of planarized, electroformed nickel microparts prior to release from the microscreen. a) Low and b) high magnification of internal microgears. c) High magnification of straight edge and corner. d) Wedge pattern used to determine the resolution limit of the replication process.

Figure 7. SEM cross-sectional photograph of an electroplated microscreen showing infill coverage of the electroplated metal over the tapered screen holes. The thin, sacrificial copper layer is visible as are dimples over some underplated areas in this example.

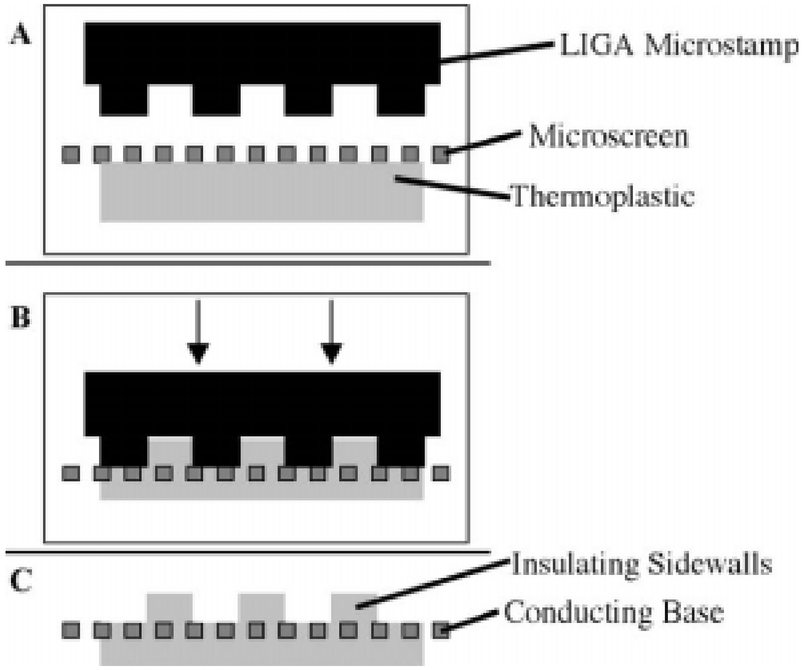
A
LIGA Microstamp
Microscreen
Thermoplastic
B
C
Insulating Sidewalls
Conducting Base

Figure 1

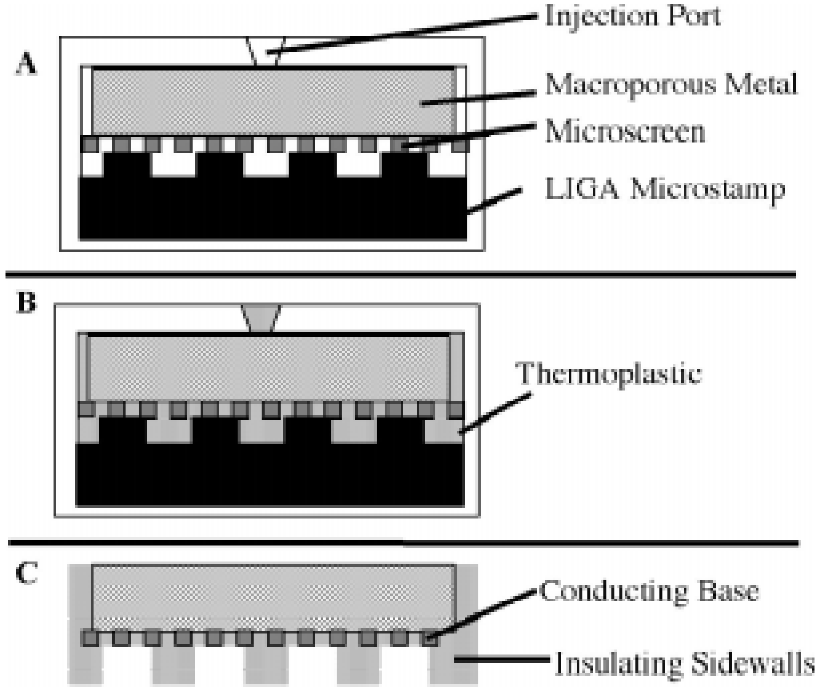
A
Injection Port
Macroporous Metal
Microscreen
LIGA Microstamp
B
Thermoplastic
C
Conducting Base
Insulating Sidewalls

Figure 2

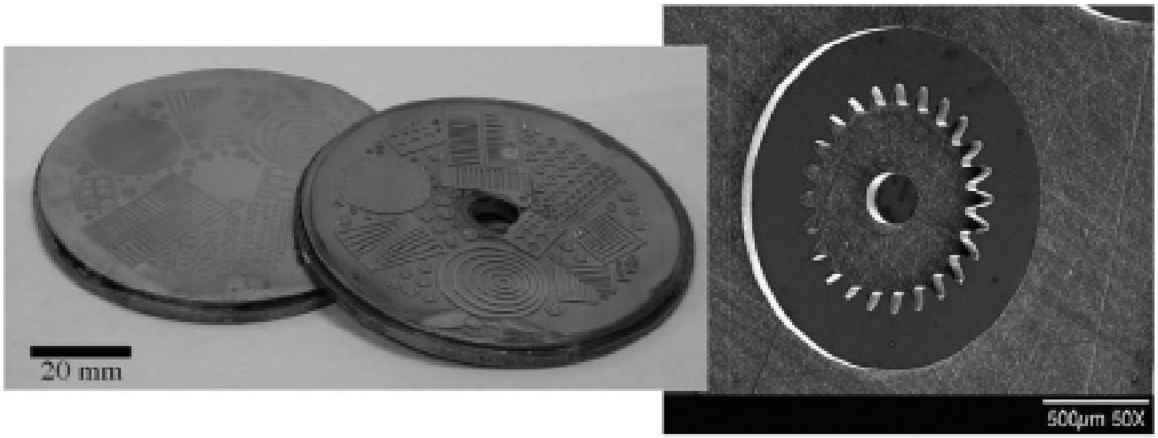

Figure 3

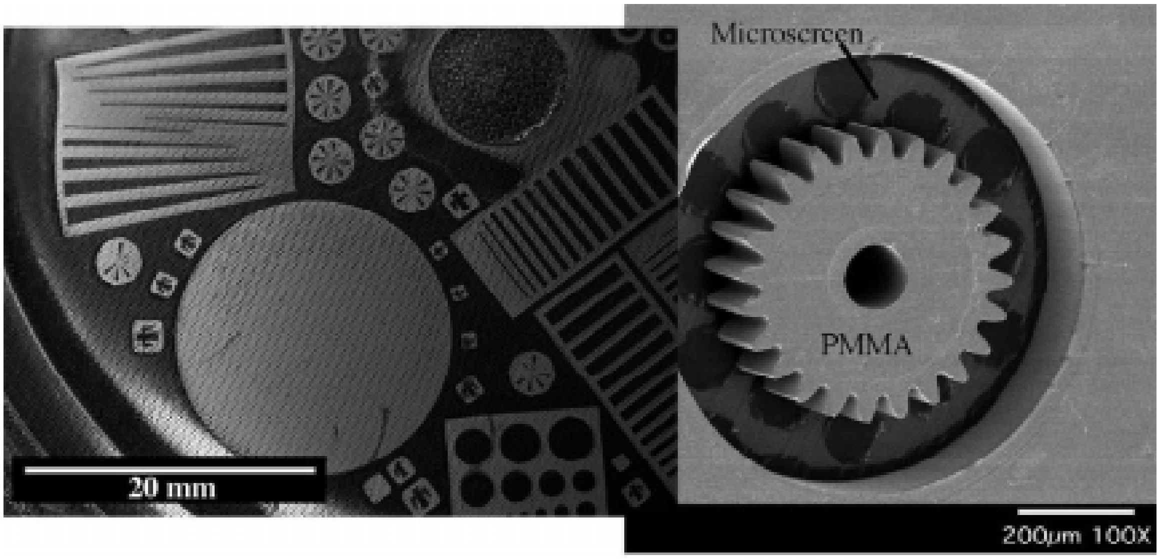

Figure 4

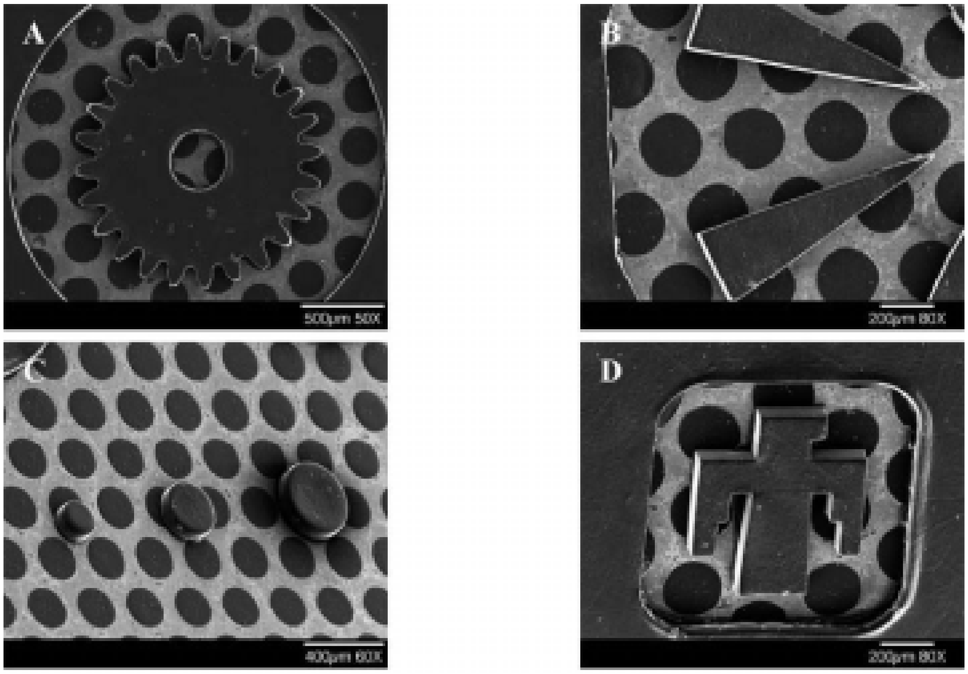

Figure 5

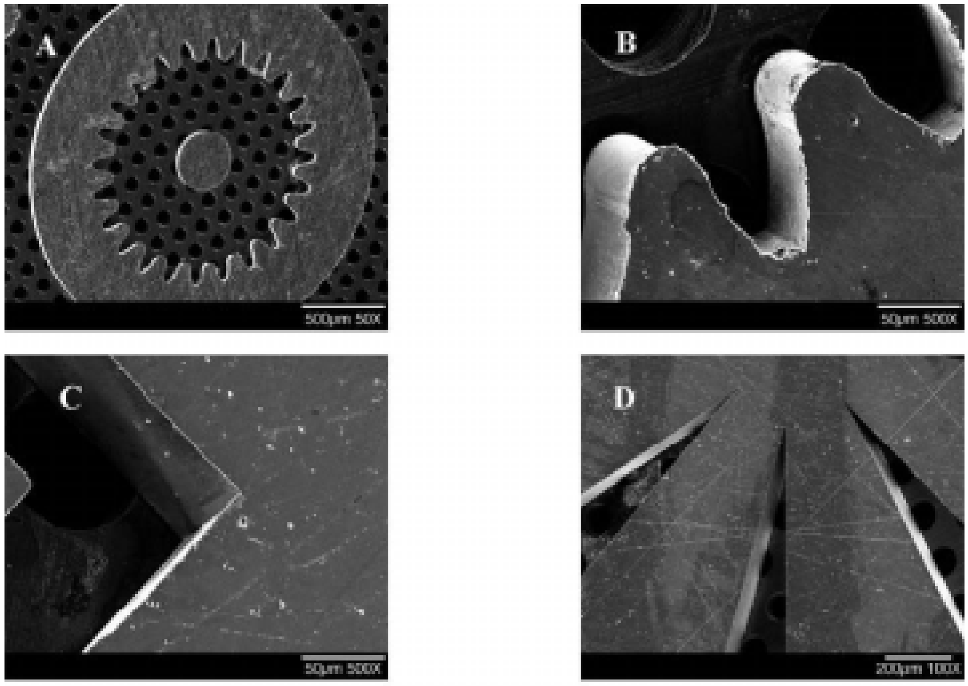

Figure 6

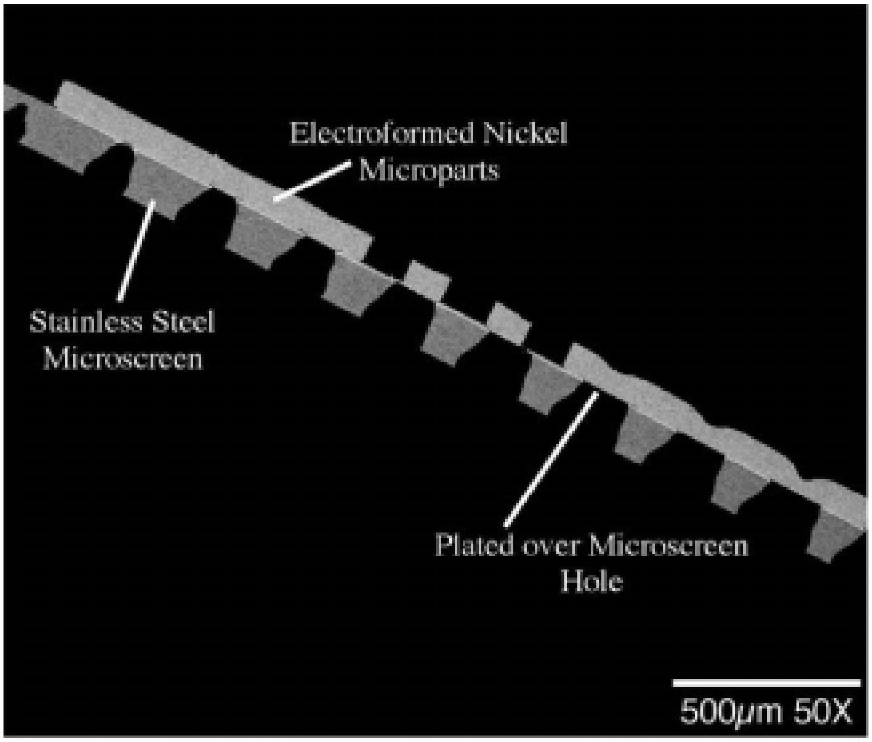
Electroformed Nickel
Microparts
Stainless Steel
Microscreen
Plated over Microscreen
Hole
500μm 50X

Figure 7